Correlation between SiO and X-ray emission in the Galactic Center

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Abstract. We present emission maps (spatial resolution ∼40") of the Sgr A molecular cloud complex at the Galactic Center (GC) in the J=2→1 SiO line, observed with the IRAM-30m telescope at Pico Veleta. We have compared our SiO(2-1) data cube with CS(1-0) maps, and we have found a correlation between the SiO/CS intensity ratio and the equivalent width of the X-ray Fe line at 6.4 keV. We discuss the SiO abundance enhancement in the two most plausible scenarios for the origin of the Fe line, which is, at the moment, under debate: fluorescence in an X-ray Reflection Nebula (XRN), or impact by Low-Energy Cosmic Rays (LECRs) followed by electronic relaxation. Both could explain the enhancement in the SiO/CS intensity ratio with the intensity of the Fe line, but both scenarios present difficulties: the first one requires a population of very small grains to produce the enhancement in the SiO/CS intensity ratio, and the second needs higher column densities than the ones derived from observations in the region.

1. Introduction

The Galactic Center (GC) contains a great variety of sources of energetic activity including a massive black hole, supernova remnants (SNRs), several massive stellar clusters, strong magnetic fields, and a strong background of X-ray emission. When X-ray radiation impinges on molecular clouds, the ionization degree increases, generating a specific chemistry in regions known as X-ray Dominated Regions (XDRs). In addition to the chemical effects, in the presence of hard X-rays one also expects to observe the iron Kα line at 6.4 keV (hereafter Fe^{o} line) from the XDR. This line is produced by fluorescence caused by X-rays or high energy particles (>7.1 keV) interacting with neutral or partially ionized iron atoms (below Fe XVII). As a result, a K-shell electron is removed from the iron atom and the filling of this inner-shell vacancy produces the fluorescent line emission at 6.4 keV. The Galactic Center (GC) shows strong emission of the Fe^{o} line, but its origin is still a matter of discussion (hard X-rays [1] vs. high energy particles [2]).

In this scenario, SiO emission is a perfect tool to study the energetic phenomena that are taking place at the GC, because it is a very well known high temperature and shock tracer of dense gas. It is well established that the SiO abundance is strongly enhanced by the sputtering

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of grains and grain mantles by shocks generated by energetic phenomena [3]. However, it has also been proposed that SiO abundance is also strongly enhanced in the GC by hard X-rays. Large scale mapping of the 200 central parsecs of our Galaxy in the J=1→0 line of SiO (with a resolution ∼2') compared with the Fe° line map obtained with the X-ray satellite *ASCA*, has shown a correlation between the spatial distribution of both emissions [4].

In this paper, we present maps of the Sgr A molecular cloud complex in the GC in the SiO(2-1) line with a higher spatial resolution (∼40"), and compare our SiO(2-1) data cube with that of CS(1-0) emission of [5]. We find a correlation between the SiO(2-1)/CS(1-0) intensity ratio and the Equivalent Width (EW) of the Fe° line. This suggest that the SiO abundance is enhanced as a result of the same energetic mechanisms that lead to emission in the Fe° line. Finally, we discuss the SiO abundance enhancement in the context of the two most plausible scenarios proposed in the literature for the origin of the Fe° line: fluorescence in an X-ray Reflection Nebula (XRN), or impact by Low-Energy Cosmic Rays (LECRs) followed by electronic relaxation.

2. Observations and results

The mapping of the J=2→1 line of SiO was carried out with the IRAM−30 m radio telescope at Pico Veleta (Spain). The half-power beam width (HPBW) of the telescope was 29" at the rest frequency of the transition (86846.96 MHz). Within the same bandwidth, we simultaneously observed the J=1→0 line of $H^{13}CO^+$ at 86754.33 MHz.

The bulk of the data were observed in raster mode with the reference position located far away from the Galactic plane. The positions of the raster grid were separated by 40", although in some regions this separation was 20". Some selected regions (including the Thermal Filaments) were observed using the On-The-Fly (OTF) mode and they were fully sampled. All the data were finally combined and re-gridded using a Gaussian kernel with a HPBW of 40". The final channel maps (49×49 pc at the GC distance of 8.5 kpc) cover the main features in the Sgr A complex, including the whole molecular region with Fe° line emission observed by *Chandra* [2].

Additionally, we also observed the J=3→2 line of SiO at selected positions (marked with white circles and ellipses in Fig. 1). The HPBW of the telescope at the rest frequency of this transition (130268.61 MHz) was 19".

In Figs. 1 and 2 we show the SiO J=2→1 and CS J=1→0 [5] emission maps as contour levels for three different negative and positive radial velocities, respectively, superimposed on the image of the EW of the Fe° line emission [2]. This line is only associated with a subset of the molecular clouds located along any given line of sight, which can be identified by their radial velocities [4]. Unfortunately, the X-ray spectroscopy lacks the energy resolution necessary to compare directly the Fe° and the molecular line emission for different radial velocities.

3. Identification of the molecular clouds associated with the Fe° line.

To identify which molecular radial velocities are associated with the Fe° line emission, we have used the criterion of the best morphological coincidence between the CS and the Fe° line emissions. We have used the CS emission because it is one of the best tracers of high density gas, it is moderately affected by shocks [6], and it seems to survive UV radiation fields [7]. Therefore, we expect that CS emission will trace the large column densities of neutral material required to produce the Fe° line emission [4]. We have found six velocity channels in the CS maps in which the CS distribution meets the morphological criterion of a match with the Fe° line emission. Three of them correspond to the −30 km s^{-1} molecular cloud [8] with central velocities of −22.5, −17.5, and −12.5 km s^{-1} (Fig. 1), and the other three have positive radial velocities of 17.5, 27.5, and 42.5 km s^{-1} (Fig. 2) and are associated with the G0.11−0.11 molecular cloud [9].

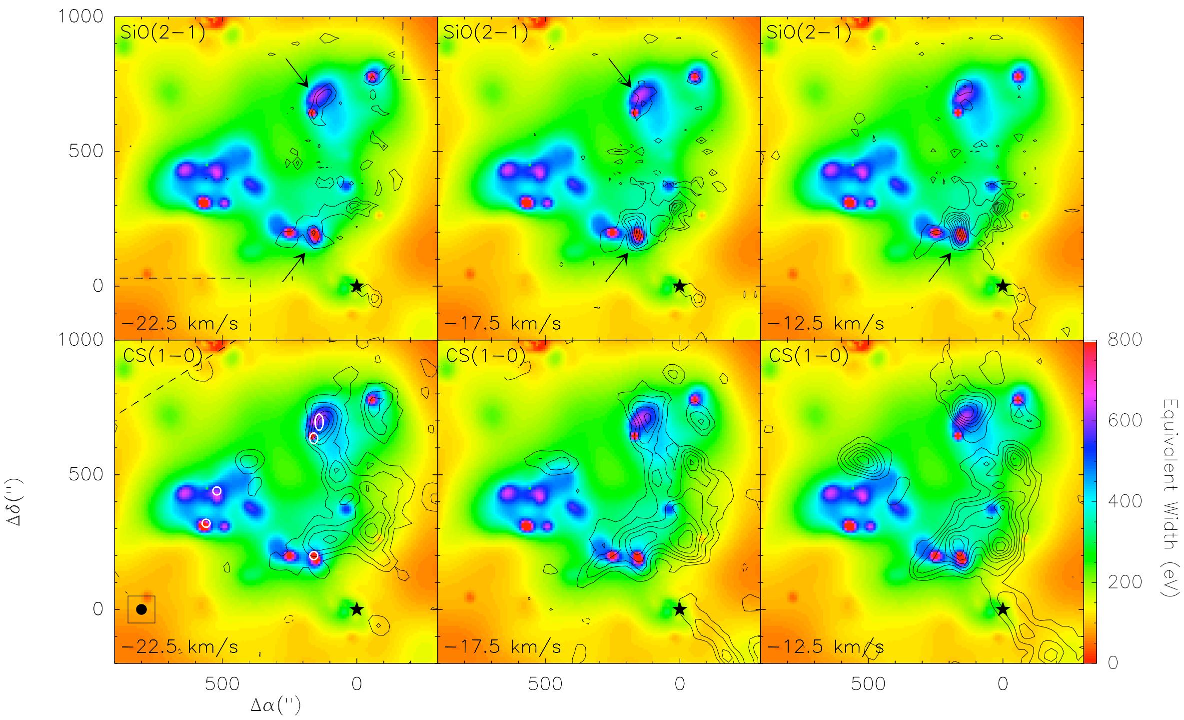

Figure 1. Spatial distribution of the SiO(2-1) (upper panels) and CS(1-0) (lower panels) line emission in the negative velocity channels superimposed on the image of the Fe^{o} line [2] shown in color scale (the EW of this line). This scale is saturated to show more clearly the maxima of the intensity of the Fe^{o} line. Contour levels of the SiO(2-1) emission (in T_A^* scale) are from 0.12 (3σ) in steps of 0.10 km s^{-1}. Contour levels of the CS(1-0) emission are from 0.30 (3σ) in steps of 0.20 km s^{-1}. The central velocities of the line emission maps are shown in the bottom left corner of each panel. The velocity width per channel is 5 km s^{-1}. The filled star marks the position of Sgr A*, which is the origin of the offsets coordinates in arc seconds. The dashed lines show the boundaries of the molecular maps, whose reconstructed beam size is drawn inside a square in the CS(1-0) left panel (∼40"). In this panel we also show the locations of the regions (white circles and ellipses) for which we have derived the physical conditions of the molecular gas (Table 1). The black arrows of the upper panels point out the regions of the molecular clouds where we find the best morphological coincidence.

4. The SiO/CS correlation with the Fe^{o} line.

In order to establish whether the SiO abundance is enhanced in the molecular clouds with strong Fe^{o} line emission, we have calculated the SiO/CS line intensity ratio for all selected velocity channels. Fig. 3 (black dots) shows the SiO/CS line intensity ratio as a function of the EW of the Fe^{o} line. First, we have spatially re-sampled the Fe^{o} EW map to the same number of pixels than the molecular emission maps (which were previously smoothed and re-sampled to the same velocity resolution, 5 km s^{-1}). Then, for the pixels with Fe^{o} line intensities greater than 500 eV, we have determined the SiO/CS ratio from one pixel. For the regions where the Fe^{o} line emission is more diffuse, we have averaged over 9, 20, and 28 pixels depending on the strength of the CS emission. The error bars (1σ) were derived by propagating the root-mean-square (rms) noise of the CS and SiO spectra. Points with a vertical arrow represent upper limits to the SiO

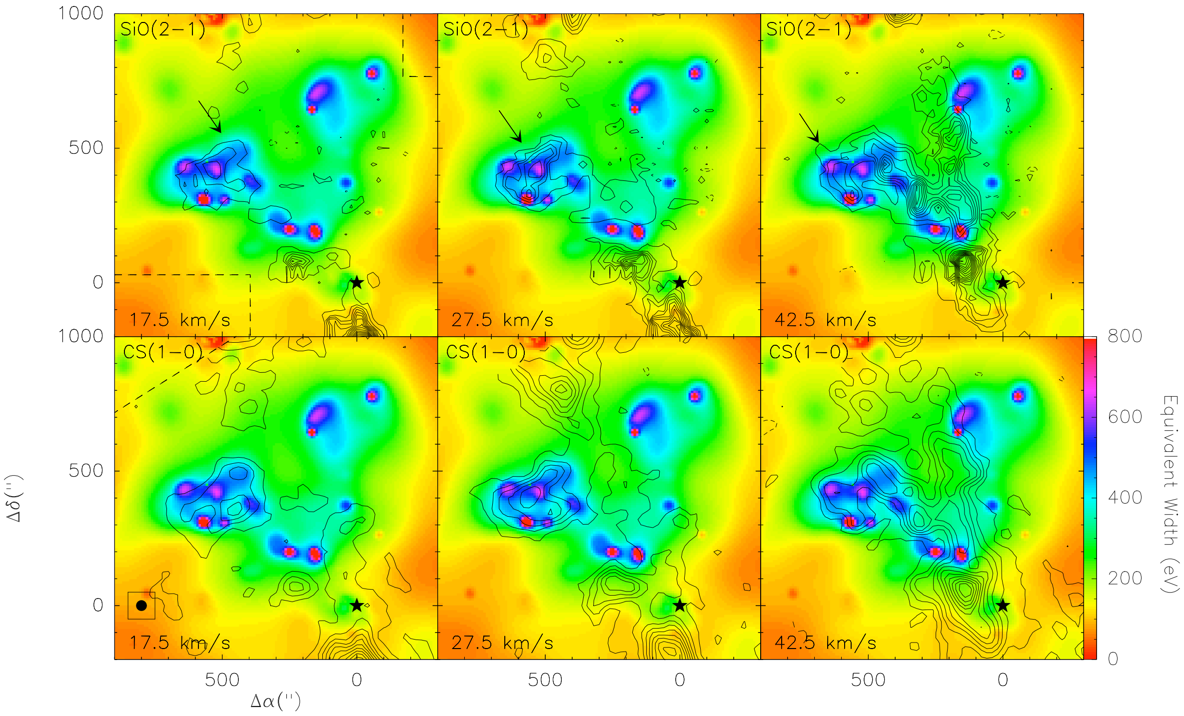

Figure 2. The same as Fig. 1, but for the positive velocity channel maps. Contour levels of the SiO(2-1) emission are from 0.12 (3σ) in steps of 0.15 km s^{-1}. Contour levels of the CS(1-0) emission are from 0.30 (3σ) in steps of 0.30 km s^{-1}.

emission at a 3σ level.

As observed by [4] for the Sgr B complex, we find a systematic increase of the SiO/CS line ratio as a function of the strength of the Fe^{o} line. The SiO/CS ratio increases by more than one order of magnitude when the Fe^{o} EW changes from 200 to 700 eV. There is, however, a substantial dispersion in the SiO/CS ratio when the EW is larger than 500 eV. In fact, the largest SiO/CS ratio of ∼0.8 is not found for the largest Fe^{o} EWs. The data seem to show a bimodal distribution with two sets of data points bifurcating at ∼650 eV. It is interesting to note that all the points in the data set with the highest SiO/CS ratio that seem to follow a steeper slope are located in the eastern region of the G0.11−0.11 molecular cloud, where [9] proposed that an interaction of the cloud with the intense magnetic field traced by the Radio Arc could be taking place.

The blue triangles in Fig. 3 show the averages of all the individual values of the SiO/CS ratio when binned to 100 eV, except for the two points with the highest EW, which have been averaged together. The error bars represent the standard deviation of the averaged value. This figure shows a good correlation between the Fe^{o} line and the averaged SiO/CS abundance ratio. The SiO/CS line ratios should provide a very good approximation of the column density ratios [4], since SiO and CS have similar dipole moments and energy level distributions. Then, the SiO/CS line ratios do not depend strongly on the physical conditions if the emission is optically thin.

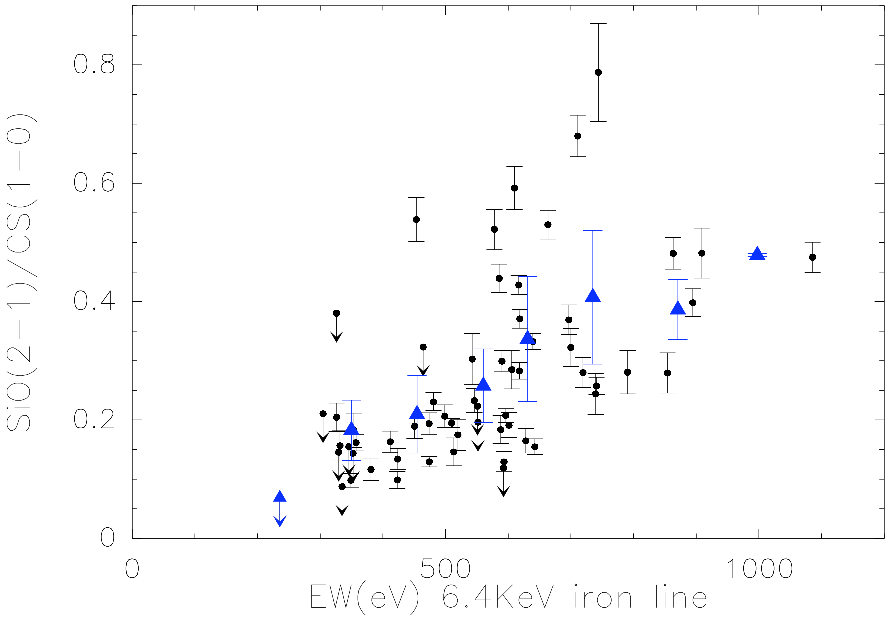

Figure 3. Correlation between the SiO(2-1)/CS(1-0) line intensity ratio and the equivalent width of the Fe^{o} line in the Sgr A complex.

5. Physical conditions of the gas.

In order to evaluate the physical conditions of the gas, we selected five positions at the Fe^{o} line intensity peaks, shown with white circles (individual spectra) and ellipses (averaged spectra) in the bottom left panel of Fig. 1.

To derive the excitation temperature (T_{ex}), opacity (τ) and column density of the SiO emission, as well as the volume density (n_{H_2}) of the medium, we have fitted the J=2→1 and J=3→2 transitions of SiO using a Large Velocity Gradient (LVG) excitation code. We assume a kinetic temperature $T_K \sim 70$ K [10]. The results from the LVG model for the five selected positions are shown in Table 1. The excitation is clearly sub-thermal ($T_{ex} << T_K$), the emission is optically thin ($\tau < 1$), and the SiO column densities range from 0.8 to $6 \cdot 10^{13}$ cm^{-2}. We have also derived the $H^{13}CO^+$ column density ($N_{H^{13}CO^+}$) applying the LVG model, with the physical conditions derived from the SiO transitions. $N_{H^{13}CO^+}$ ranges between 1.8 and 8 $\cdot 10^{12}$ cm^{-2}.

Taking into account the isotopic ratio $^{12}C/^{13}C$ for the GC of ∼20 [11], and a fractional abundance $X_{HCO^+} = N_{HCO^+}/N_{H_2} \sim 10^{-8}$ [12], we derive $N_{H_2} \sim (0.4-1.6) \cdot 10^{22}$ cm^{-2} (7^{th} column of Table 1).

6. Discussion.

The spatial variations of the SiO/CS ratios could be due to variations in the abundances of CS, SiO or in both. However, the CS abundance seems to be rather uniform in the GC clouds, independent of the type of dominating chemistry. The changes in the SiO/CS line ratio with the Fe^{o} line intensity suggest that the SiO abundance could be enhanced by the same mechanism that also give rise to the Fe^{o} line, whose origin is subject to debate [1, 2]. In the following, we will discuss briefly the different mechanisms that could explain the observed correlation between the SiO/CS line intensity ratio and the Fe^{o} line.

Table 1. Physical conditions of the gas and molecular abundances derived at the selected positions shown in Fig. 1.

offset (")	N_{SiO} ($\times10^{13}$ cm^{-2})	τ	T_{ex} (K)	n_{H_2} ($\times10^5$ cm^{-3})	$N_{H^{13}CO^+}$ ($\times10^{12}$ cm^{-2})	N_{H_2} ($\times10^{22}$ cm^{-2})
(140, 695)	1.0	0.11	6	1.2	4	0.8
(160, 635)	0.8	0.08	8	2.2	1.8	0.4
(160, 200)	2.5	0.3	6	1.0	8	1.6
(560, 320)	6	0.4	5	0.6	7	1.4
(520, 440)	3	0.19	7	1.8	7	1.5

6.1. Low Energy Cosmic Rays (LECRs)

[13] suggested that the Fe^o line emission could be explained by impact ionization of molecular gas by low-energy cosmic-ray electrons (LECRs) with energy of $\sim$30 keV. [2] have applied this model to several dense molecular clouds in the GC with Fe^o line emission. Basically, [2] calculate the production rate of the Fe^o photons associated with the injection of electrons per unit energy interval and time, into a cloud with a given column density. Their predicted flux for the Fe^o line is one order of magnitude smaller than that observed for the Sgr A clouds near the Radio Arc. Only very large column densities of $\sim10^{24}$ cm^{-2} could fit the observations. However, such a high column density for the molecular gas is incompatible with our estimates by nearly two orders of magnitude (see Table 1).

In this scenario, the SiO enhancement could be produced by the same process that also accelerates the electrons, i.e., shocks generated by SNe [14]. Metal-rich ejecta blobs from a SN that propagates through the ambient medium create shocks, which accelerate the electrons. Internal shocks are also generated within the ejecta blobs. The population of high energy electrons will irradiate the ejecta blobs and generate the Fe^o line emission. As ions and electrons are accelerated to high energies, they will penetrate deep into the ejecta blobs enhancing the grain erosion. Also, the shocks propagating into the molecular cloud and into the ejecta blobs will sputter and erode the grains, ejecting Si atoms or SiO molecules to the gas phase.

In the Sgr A complex, there are at least two identified SNRs: Sgr A East and G359.92$-$0.09 [15]. However, at the expected interaction sites of these SNRs with the 50 and 20 km s^{-1} molecular clouds, respectively, the Fe^o line does not show any excess emission, although the SiO/CS value is comparable to the highest values found in Fig. 3.

6.2. X-ray Reflection Nebula (XRN).

In the XRN scenario, the Fe^o emission is a consequence of the illumination of the GC molecular clouds by external X-ray sources, together with Thomson scattering and/or absorption of these X-rays by the gas and dust in the clouds [16]. Those authors propose that a past episode of bright X-ray emission from some source in the GC, possibly the central super-massive black hole, Sgr A*, could be the illuminating source.

According to this hypothesis, the enhancement of the SiO abundance could be due to the interaction of hard X-ray photons (E >7.1 keV) with gas and dust grains. The photoelectrons produced by the X-rays will deposit their energy while they traverse the grains, giving rise to temperature fluctuations. In the case of small grain sizes, $\sim$10 Å, the peak temperature could be as high as 1000 K, making possible the evaporation of grains, which will release atomic Si or SiO to the gas phase. The fraction of Si atoms evaporated from one grain could be as high as

0.1% [17, 4].

However, to produce the observed SiO abundance enhancements, there must be a significant population of very small silicate grains. [18] have shown that in the diffuse interstellar medium the fraction of silicate mass depleted onto very small grains could be as high as 10% for grains with $a \leq 15$ Å. From our estimations of N_{H_2} and N_{SiO} at the five positions of the maxima in the X-ray emission (Table 1), we derive a SiO fractional abundance of $\sim 10^{-9}$. Taking into account the value for the elemental abundance of silicon of [19] ($X_{Si}=n_{Si}/n_H \sim 3.55 \cdot 10^{-5}$), considering that the metallicity at the GC is likely twice the solar value [20] and [HI]/[H_2] $\sim$0.05 in the central 500 pc of the Galaxy [21], and assuming that most of the Si is ejected from grains in the form of SiO, we conclude that with only a small fraction of atoms evaporated from small grains ($\sim$0.01%), we could reproduce the observed fractional abundances.

Additional support for the XRN scenario comes from the variability in the intensity and morphology of the 4−8 keV X-ray emission that [22] have reported in the Sgr A complex. They claim that matter (low energy electrons or ejecta blobs from SNe) would propagate too slowly to produce the observed variability in only 3 years.

7. Conclusions

We have mapped the Sgr A region in the J=2→1 line of SiO, and have found that the SiO/CS intensity ratio in the Sgr A region is correlated with the equivalent width of the neutral or low-ionization Fe Kα fluorescence line at 6.4 keV. The SiO abundance is enhanced by nearly one order of magnitude toward the regions with strong emission in the 6.4 keV Fe line. We have discussed the two mechanisms previously proposed in the literature to explain the 6.4 keV Fe line in the context of the SiO abundance enhancement found in this paper, namely the X-ray Reflection Nebula (XRN) and the Low-Energy Cosmic-Ray (LECR) scenarios. The LECR scenario seems to explain the SiO enhancement in a natural way in the case that the electron acceleration has been produced in shocks associated with SNRs propagating through dense molecular clouds. The main weaknesses of this hypothesis are the high gas column density required to produce the flux of the 6.4 keV Fe line, and the existence of molecular clouds that show evidence of interaction with SNRs but which do not correlate with the 6.4 keV Fe line intensity. In the XRN scenario, the SiO enhancement can only be explained by the evaporation of very small silicate grains, the presence of which is still under debate. The reported variability in the 6.4 keV Fe line intensity supports this scenario.

Acknowledgments

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References

[1] Koyama K, Inui T, Matsumoto H and Tsuru T G 2008 *PASJ* **60** S201
[2] Yusef-Zadeh F, Muno M, Wardle M, and Lis D C 2007 *ApJ* **656** 847
[3] Martín-Pintado J, Bachiller R and Fuente A 1992 *A&A* **254** 315
[4] Martín-Pintado J, Rodríguez-Fernández N J, Fuente, A and Planesas P 2000 *A&A* **356** L5
[5] Tsuboi M, Handa T and Ukita N 1999 *ApJS* **120** 1
[6] Requena-Torres M A, Martín-Pintado J, Rodríguez-Franco A, Martín S, Rodríguez-Fernández N J and de Vicente P 2006 *A&A* **455** 971
[7] Martín S, Requena-Torres M A, Martín-Pintado J and Mauersberger R 2008 *ApJ* **678** 245

[8] Serabyn E and Güsten R 1987 *A&A* **184** 133
[9] Tsuboi M, Ukita N and Handa T 1997 *ApJ* **481** 263
[10] Hüttemeister S, Wilson T L, Bania T M and Martín-Pintado J 1993 *A&A* **280** 255
[11] Wilson T L and Rood R T 1994 *ARA&A* **32** 191
[12] Irvine W M, Goldsmith P F and Hjalmarson Å 1987 *Interstellar Processes* ed D J Hollenbach and H A Thronson Jr (Dordrecht: Reidel) p 561
[13] Valinia A, Tatischeff V, Arnaud K, Ebisawa K and Ramaty R 2000 *ApJ* **543** 733
[14] Bykov A M 2002 *A&A* **390** 327
[15] Coil A L and Ho P T P 2000 *ApJ* **533** 259
[16] Koyama K, Maeda Y, Sonobe T, Takeshima T, Tanaka Y and Yamauchi S 1996 *PASJ* **48** 249
[17] Voit G M 1991 *ApJ* **379** 122
[18] Li A and Draine B T 2001 *ApJ* **550** L213
[19] Yan M 1997 Thesis, Harvard University, Cambridge, Massachusetts
[20] Morris M and Serabyn E 1996 *ARA&A* **34** 645
[21] Güsten R and Philipp S D 2004 *Proc. of the 4th Cologne-Bonn-Zermatt Symp.: The Dense Interstellar Medium in Galaxies* vol 91 (Heidelberg: Springer) p 253
[22] Muno M P, Baganoff F K, Brandt W N, Park S and Morris M R 2007 *ApJ* **656** L69